Spatial Analysis of Maritime Accidents Using the Geographic Information System

Dao-Zheng Huang, Hao Hu, and Yi-Zhou Li

Despite the tremendous efforts of maritime organizations to achieve a safe and secure maritime transportation system, the losses through maritime accidents and incidents are still increasing. This paper analyzes the spatial distribution of maritime accidents occurring from January 1, 2002, to December 31, 2011, based on the Marine Casualties and Incidents module of the Global Integrated Shipping Information System. The geographic information system, an effective and efficient tool for spatial analysis with high visualization, is used to carry out the analysis. Hot-spot analysis of maritime accidents identifies the hot spots. Buffer analysis is used to calculate accidents that occurred in coastal areas. Finally, the following two important results are obtained from the analysis. First, the identification of hot spots reveals the area around the United Kingdom as the area with the greatest number of accidents and the coastal areas around East Asian countries (such as China, Japan, and South Korea) and the Mediterranean Sea as the areas with the next highest number of accidents. These results compare well with a previously published paper. Second, maritime accidents may not frequently occur in the open sea; however, accidents frequently happen in coastal areas, with 51.1% of the total accidents happening within 25 mi of the continents and 62.2% within 50 mi.

As described in the 2012 to 2017 strategic plan (*1*) for the International Maritime Organization (IMO), maritime safety has become a topic of importance to the global maritime community, with efforts being made to increase awareness of implementing procedures to improve maritime safety. As congestion of natural resources, energy, and environment on land increases, people are paying more attention to the ocean, which covers 71% of the earth's surface, for energy, food, and transportation. Shipping is the primary method of transporting materials and products onto land, accounting for 90% of international trade. However, shipping has always been recognized as a relatively risky mode, and currently people are less tolerant of maritime accidents. Analysis of maritime accidents is very valuable for authorities who try to improve maritime safety through legislation, insurance, and other entities concerned with maritime transportation.

Despite the tremendous efforts of different maritime organizations to achieve a safe and secure maritime transportation system, the losses through maritime accidents and incidents are still increasing (*2, 3*). From 2002 to 2011, thousands of reported maritime accidents occurred. The actual number of accidents could be much higher because many accidents are unreported. Maritime accidents damage property and the environment and result in human fatalities. The analysis of accidents can provide decision makers with valid and reliable information, which is vital for them to make informed and improved decisions about maritime operations (*4*). Empirical data have been the basis of most maritime accident analysis. Mullai and Paulsson proposed a grounded theory model for marine accidents analysis based on large amounts of empirical data in the Swedish Maritime Administration database (*4*). Because no database includes all accidents, some researchers try to analyze the underreporting of accidents (*5–7*). The reasons for maritime accidents are important, and the human factor cause is the most famous one. Landsburg et al. (2008) studied the art of successfully applying human systems integration (*8*). How to best apply behavioral science principles, knowledge, and analytical tools to the engineering design or improvement of systems was drawn from a number of best-practice cases. Almaz et al. developed a risk analysis model by quantifying the causal chain from instigator, to accident, and finally to consequence in the Delaware River and Bay study (*9*). In this work, a risk profile of the river was generated over time. It provides a good estimation model of the accident risk. In general, most of the research into maritime accidents focuses on the number, consequence, or the reason for the accidents (*5–7, 9*), but little work has been done on the spatial distribution of accidents, especially on a global scale. Some research has estimated risk in different geographic areas using historical accident data; unfortunately, most of them were confined to relatively small geographic areas, such as a country, a river, a strait, or a port. Dobbins and Jenkins estimated coastal maritime risk in the United States using geographic information system (GIS) data by adapting a GIS-based highway planning traffic assignment model for use in maritime risk assessment (*10*). This was an important step in quantifying maritime risk of coastal lanes using GIS layers and databases maintained by the U.S. Coast Guard, U.S. Army Corps of Engineers, and the U.S. Customs and Border Protection Agency. Although analysis of small marine areas is easier to conduct and more targeted, it cannot provide a complete overview of maritime accidents throughout the world. Yin performed statistical analysis of marine accidents and detailed the number of accidents that occurred in each of the 31 zones that comprise the whole world, where the zones are defined in accordance with the *World Casualty Statistics* (*11*). Nevertheless, no exact locations of the accidents are considered.

GIS is an effective and unique tool for spatial analysis and provides visualization of geographic data. The aim of GIS is to provide a spatial framework in which the world can be modeled, making it possible for reasonable use of its resources, and for support of decisions for sustainable development of the environment. Generally, GIS comprises three components. First, GIS has a spatial database

D.-Z. Huang and H. Hu, School of Naval Architecture, Ocean, and Civil Engineering and State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, China. Y.-Z. Li, Department of International Shipping, Shanghai Jiao Tong University, Room 1302 (HaoRan), 1954 Huashan RD, Shanghai, China. Corresponding author: H. Hu, hhu@sjtu.edu.cn.

Transportation Research Record: Journal of the Transportation Research Board, No. 2326, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 39–44.
DOI: 10.3141/2326-06

that contains data models (such as features, grid, and topology) used to describe the physical world. Similar objects are grouped into layers, and information about each object is maintained in a relational database or file (*10*). Objects are typically represented in vector format, such as points, lines, and polygons. Aerial images, such as satellite photos, can also be used in most GIS packages and are included in the database. Second, a GIS presents its data via an intelligent map. This map can also be regarded as a visualization of the database. Finally, GIS typically provides a spatial process toolbox that enables complex analysis of database objects based on their spatial locations using the current analysis module or through software written by the user or third parties. GIS has been widely used in highway planning, network analysis, and other applications.

The primary object of this paper is to analyze the spatial distribution of maritime accidents worldwide from January 1, 2002, to December 31, 2011, based on the Global Integrated Shipping Information System (GISIS) database, and provide a complete visualization of global maritime accidents. Cluster analysis and buffer analysis are used. The results of the paper identify hot-spot accident areas where resources to mitigate accidents can be focused and quantify accident rates in coastal areas where maritime agencies can focus resources on improving marine operations. The remainder of the paper is structured as follows: a review of the literature related to maritime accidents and application of GIS in maritime transportation. Next, accident data are collected and processed. Next is the spatial analysis of maritime accidents, which is the main part of the work. Hot-spot areas and accident rates in coastal areas are shown next. Finally, conclusions and recommendations for future work are provided.

LITERATURE REVIEW

Databases are the basis of maritime accident analysis. Generally speaking, three types of databases exist: public databases managed by IMO, commercial databases maintained by classification societies (e.g., Lloyd's Register), and databases maintained by a government agency. GISIS (maintained by IMO) and Lloyd's List Intelligence (LLI, maintained by Lloyd's Register) are two well-known databases in the maritime industry (*7*). The Nordic Marine Insurance Statistics database, maintained by the Nordic Association of Marine Insurers (Cefor), is available only to the Cefor administration (*5*), while the results of its statistical analyses are distributed as information. The U.S. Coast Guard, the U.S. Army Corps of Engineers, and the U.S. Customs and Border Protection agency are the main organizations administrating maritime data in America. Almaz et al. used the U.S. Coast Guard accident data of Delaware River and Bay to quantify the causal chain process (*9*). Other databases include the Swedish database, the Norwegian Maritime Directorate, and so on. As for accidents that occur very rarely with large consequences, Apostolakis (*12*) pointed out that because they generally were rare, expert judge or experimental support were critically important to evaluate their frequency.

Additional research into maritime accidents has studied underreporting of accidents (*5, 6*), statistics, and risk analysis models based on accident data. The study of underreporting of accidents aims to estimate the actual number of accidents by comparing two different databases that cover the same sample space. The following three approaches are usually applied to estimate the actual number of accidents: the best case scenario method, the capture–recapture method, and the Bayesian conditional probability method (*7*). Regression and clustering analysis are frequently adopted statistical methods. Yip proposed a binomial regression model based on historical accident data of years 2001–2005 to analyze port traffic risks in Hong Kong Harbor (*13*). Shahrabi and Pelot carried out a hierarchical cluster analysis performed on a sample of 2,002 reported fishing incidents (*14*). Yin conducted a relatively comprehensive quantitative risk assessment for maritime safety management based on the GISIS and world casualty statistics of Lloyd's Register (*11*). Logistic regression is used for statistics of the accidents. Application of methods developed in other domains, such as Bayesian Network and game theory, have also been used to analyze accident rates. Kuroda et al. proposed a mathematical risk model for estimating the probability of collision of vessels passing through a certain channel (*15*). The model takes into account the traffic characteristics such as volume, vessel particulars, and sailing speed, as well as a channel's width, length, and the centerline. The proposed model is calibrated and tested on the basis of collision statistics for channels and straits in Japan.

In the United States, the Vanderbilt Center for Transportation Research has completed a series of research on applying GIS to maritime transportation including hazardous material transportation, inland water transportation, and coastal sea lanes transportation (*16–18*). Dobbins and Abkowitz developed an inland marine transportation risk management information system based on the integration of GIS, database management systems, global positioning systems, and the Internet, which enables route responders to view incident details via an Internet GIS map service when accidents occur (*16*). Martin et al. developed a GIS-based decision support system to effectively manage the risks associated with accidental or intentional releases of a hazardous material into an inland waterway (*17*). This decision support system enabled responders in identifying, responding to, and mitigating the effects of chemical release incidents. Dobbins and Abkowitz used GIS to analyze inland marine casualty data in the United States. (*18*). Additionally, Fedra and Feoli summarized the major tools of spatial analysis as GIS and remote sensing, spatially distributed simulation modeling and optimization, and expert systems, as well as their integration and application to coastal zone management (*19*). Goralski and Gold took advantage of the developments in computer graphics and GIS technologies to help tackle the main cause of marine accidents—human errors—by providing navigational aid and decision support to mariners (*20*).

DATA COLLECTION AND PROCESSING

Using GISIS to Examine Ship Casualties

GISIS is a comprehensive marine information system managed by IMO. Marine Casualties and Incidents is one of the 15 modules in GISIS, which contains two kinds of information collected on ship casualties. The first category of information is made of factual data collected from various sources, and the second category of data is made of more elaborate information based on the reports received at IMO of investigations into casualties which may include full investigation reports to be analyzed by the IMO or reporting forms annexed to MSC-MEPC.3/Circ.3. For the purpose of collecting information on ship casualties to populate the GISIS casualty module, the IMO selects ship casualties according to the following classification: very serious casualties, serious casualties, less serious casualties, and marine incidents (*21*). Very serious casualties are

TABLE 1 Data Structure

Data Field	Description
Reference	Unique accident identification
Ships involved	Ships that are involved in the accident
Accident date	The exact day of the accident
Location	General place of the accident
Longitude	The exact longitude of the accident
Latitude	The exact latitude of the accident

casualties to ships that involve total loss of the ship, loss of life, or severe pollution. Serious casualties refer to casualties to ships that do not qualify as very serious casualties and which involve a fire, explosion, collision, grounding, contact, heavy weather damage, ice damage, hull cracking, or suspected hull defect, etc., resulting in immobilization of main engines, extensive accommodation damage, severe structural damage, pollution (regardless of quantity), or a breakdown necessitating towage or shore assistance. Less serious casualties are casualties to ships that do not qualify as very serious casualties or serious casualties, and for the purpose of recording useful information also include marine incidents that themselves include hazardous incidents and near misses.

From a search in the database from January 1, 2002, to December 31, 2011, 4,092 accidents were found with data elements shown in Table 1.

To implement spatial analysis in ArcGIS (a GIS platform that includes three parts, ArcMap, ArcCatalog, and ArcToolbox), the longitude and latitude of the incidents are necessary. However, some accidents lack the data. After filtering the incidents with no coordinates, about 1,697 incidents were obtained.

Data Processing and Preliminaries to Spatial Analysis

It is obligatory to change the format of coordinate data in degrees, because coordinate data in degrees format of GISIS include degree, minute, and second, while GIS only recognizes coordinate data such as 110.15. Table 2 presents the transformation rules and examples from GISIS data to data that can be recognized by ArcGIS. The transformation is a preliminary step of the spatial analysis.

TABLE 2 Data Transforming Rules and Examples

GISIS	ArcGIS
Transforming Rules	
AAA° BB.CC′	AAA + BB.CC/60
E	+
W	–
N	+
S	–
Examples	
150° 08.90′ E	150.15
110° 09.00′ W	–110.15
21° 48.00′ N	21.80
36° 46.10′ S	–36.77

SPATIAL ANALYSIS USING GIS

GIS is a system tool designed to efficiently capture, store, manipulate, analyze, manage, and present all types of geographical data (*22*). In the simplest terms, GIS is the merging of cartography, statistical analysis, and database technology. Compared with other information systems, the most important character of GIS is its ability to address geographic data and display the results on the map with high visualization. GIS is widely used in different areas such as agriculture, environment, real estate, transportation, and national defense. This study uses the software of ArcGIS 10, consisting of three parts: ArcMap, ArcCatalog, and ArcToolbox. ArcMap is used to process maps; ArcCatalog is a tool to manage Geodatabase, and ArcToolbox is the integrated module to carry out analysis functions.

GIS spatial analysis is a rapidly developing field, and GIS packages are increasingly including analytical tools as standard built-in features, as optional toolsets, as add-ins, or as analysts. In many instances, these are provided by the original software suppliers (commercial vendors, or collaborative noncommercial development teams), while in other cases facilities have been developed and are provided by third parties. Furthermore, many products offer software development kits (SDKs), programming languages, and language support, scripting capabilities and special interfaces for developing one's own analytical tools or variants. The increased availability has created a new dimension to business intelligence termed "spatial intelligence," which, when openly delivered via intranet, democratizes access to geographic and social network data. GIS spatial analysis has also become a key element for security intelligence.

If one assumes that the accidents that were underreported or lacked longitude and latitude data were stochastic, the distribution characteristics of the existing accidents could somewhat represent the situation of entire accidents.

ArcGIS 10 was used as a spatial analysis platform for GIS operations and mapping. Figure 1 illustrates the framework of the analysis process. The process can mainly be divided into two steps. The first step was data collecting, filtering, transforming, and storing. The second step was spatial analysis by ArcToolbox, with the results then displayed in ArcMap.

The first step was provided in the previous section. In the second step, the world map was used as the basic map. Next, the accident

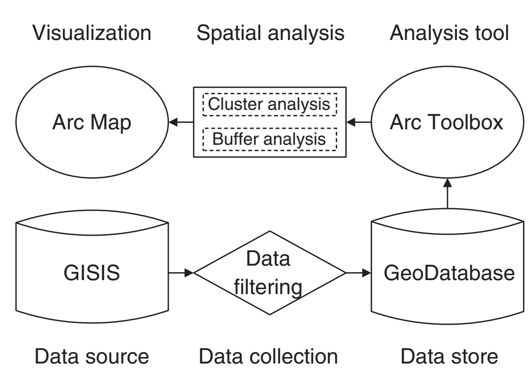

FIGURE 1 Spatial analysis framework of maritime accidents.

data were loaded into the software. To analyze those accidents in coastal areas, accidents were selected by their distance from the coast. Accidents within 25 and 50 mi from the coastline were selected.

Hot-Spot Analysis of Maritime Accidents

A map was divided into 10 ∗ 20 fishnets by creating the fishnet tool in ArcToolbox to do the hot-spot analysis. A new layer named fishnet was created. Then, the accident layer was connected to the fishnet layer; this connection created a new layer, named fishnet_SpatialJoin. In the layer fishnet_SpatialJoin, there was a data field named Joined_Count, which represented the number of maritime accidents in a particular fishnet. Finally, a hot-spot analysis was done on the layer of fishnet_SpatialJoin, according to the Joined_Count attribute.

Notation

x_i = value of data field Joined_Count in ith feature of layer fishnet_SpatialJoin,
w_{ij} = spatial weight between x_i and x_j,
$\bar{X}$ = average value of x_i, and
Z_j = Z-score of jth feature; both a big z-score in positive value and a small z-score in negative value represents a high cluster.

Calculation of Z_j

$$\bar{X} = \frac{\sum_{1}^{200} x_i}{n} \tag{1}$$

where $i = 1, 2, \ldots, 200$.

$$Z_j = \frac{\sum_{i=1}^{200} w_{ij} * x_{ij} - \bar{X} * \sum_{i=1}^{200} w_{ij}}{\sqrt{\left(\frac{\sum_{i=1}^{200} x_i^2}{n} - \bar{X}^2\right) * \left(\frac{n * \sum_{i=1}^{200} w_{ij}^2 - \left(\sum_{i=1}^{200} w_{ij}\right)^2}{n-1}\right)}} \tag{2}$$

where $j = 1, 2, \ldots, 200$.

Buffer Analysis

Buffer analysis is used for identifying areas surrounding geographic features. The process involves generating a buffer around existing geographic features and then identifying or selecting features based on whether they fall inside or outside the boundary of the buffer. In this work, buffer analysis was carried out to the continent layer. Then maritime accidents inside the buffer area were counted to analyze the accident rates in coastal areas. The accidents within 25 and 50 mi of the coastline are selected. The results are shown in the next section.

DISCUSSION OF RESULTS

After analysis in ArcGIS 10, the spatial distribution of maritime accidents in the world is obtained and shown in Figure 2. The z-scores, multiples of standard deviation, of the areas in red are more than 2.58, which means that the areas are hot spots. It can be figured out that the area around the United Kingdom has the largest number of accidents. The coastal area of East Asian countries (i.e., China, Japan, and South Korea) and the Mediterranean Sea are the other two areas with a large number of accidents. These results compare favorably with previous work.

Yin did a statistical analysis of maritime accidents from 1993 to 2008 based on the world casualty statistics and the GISIS database

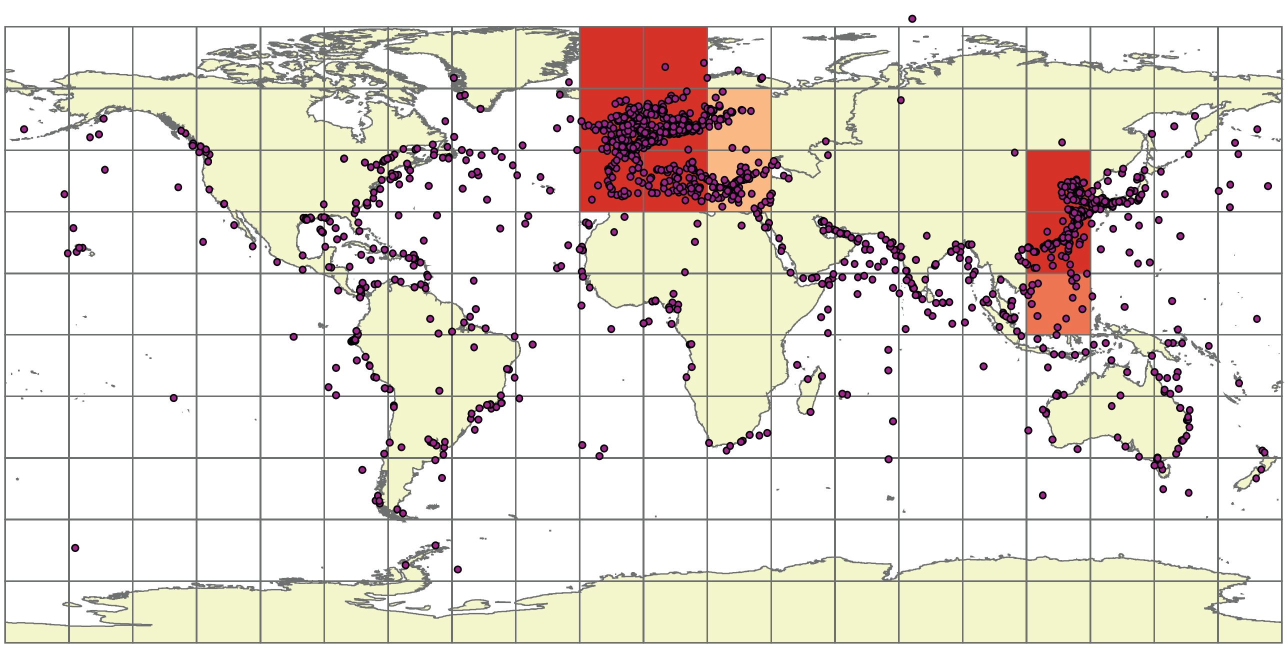

FIGURE 2 Hot-spot analysis of maritime accidents.

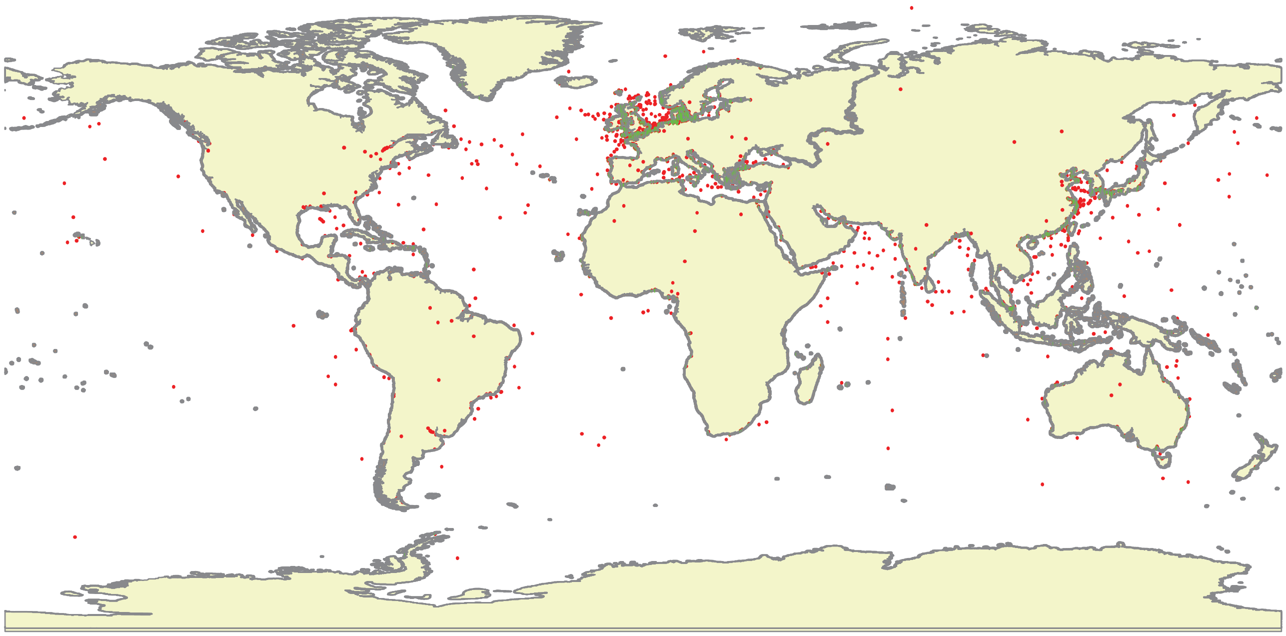

FIGURE 3 Maritime accidents within 25-mi buffer of continents.

(*11*). The hot-spot areas identified in this research are compared with Yin's paper. Yin's regions of highest accident frequency are the following zones: the areas around the United Kingdom; East Asian countries such as China, Japan, and South Korea; and the South China Sea. The first two areas, the areas around the United Kingdom and the East Asian countries such as China, Japan, and South Korea, are the same as the results in this research, while the third area is different. However, it is found that in Yin's paper the Mediterranean Sea is divided into two zones. If the percentage of accidents of the two zones are added together, the result is more than that of the South China Sea. Therefore, the third high-frequency accident area in Yin's paper is also the Mediterranean Sea. Yin's paper included all the data in the GISIS, both with and without longitude and latitude.

The accidents within 25 mi of the coastline are selected. They are marked with the green spots in Figure 3. Eight hundred and sixty-eight accidents are found within 25 mi of the coastline, accounting for 51.1% of the total accidents.

Similarly, the green spots in Figure 4 show the accidents within 50 mi of the coastline; 1,055 accidents are within 50 mi of the

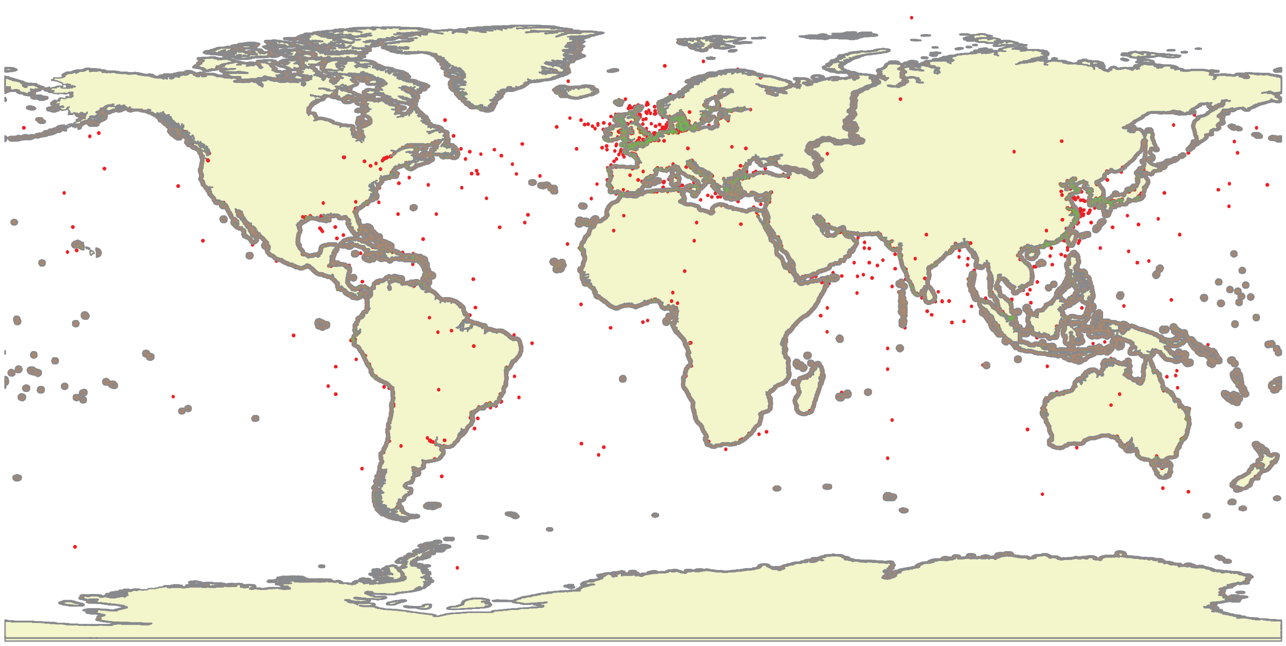

FIGURE 4 Maritime accidents within 50-mi buffer of continents

coastline. This accounts for 62.2% of the total accidents. Such results are rather useful for the coast management organizations.

CONCLUSION

This paper conducted a spatial analysis of worldwide maritime accidents based on the GISIS database. Three important conclusions are drawn as follows:

- Hot spots of the accidents are identified. The area around the United Kingdom is the area with the greatest number of accidents, and the coastal areas around East Asian countries (such as China, Japan, and South Korea) and the Mediterranean Sea are the areas with the next highest number of accidents. Further research is recommended to focus on these three areas to find the reason why there are so many accidents here and to reduce the number of accidents.
- Maritime accidents may not frequently occur in the open seas. However, there exists a high probability for them to happen at ports, coastal areas, or narrow waterways. According to this research, 51.1% of the total accidents were located within 25 mi of the coastline, and 62.2% of the total accidents were located within 50 mi of the coastline.
- GIS has made it convenient and easy to calculate the number of accidents in coastal areas. It may be very difficult and fussy to conduct this process by other statistical methods.

Because of the incompleteness of the maritime accident data, further work on the data collection should be done in the future. For example, if enough funds are provided, the Lloyd's List Intelligence casualties should be included in the data analyzed.

REFERENCES

1. International Maritime Organization. Strategic Plan for the Organization (for six-year period 2012 to 2017). Resolution A. 1037 (27), Nov. 22, 2011, pp. 3–4.
2. Trucco, P., E. Cagno, F. Ruggeri, and O. Grande. A Bayesian Belief Network Modelling of Organisational Factors in Risk Analysis: A Case Study in Maritime Transportation. *Reliability Engineering and System Safety,* Vol. 93, 2008, pp. 823–834.
3. Soma, T., G. Fuglerud, and H. Jones. Safety Excellence—Safety That Lasts. *DNV Maritime Solutions,* pp. 1–4.
4. Mullai, A., and U. Paulsson. A Grounded Theory Model for Analysis of Marine Accidents. *Accident Analysis and Prevention,* Vol. 43, 2011, pp. 1590–1591.
5. Hassel, M., B. E. Asbjornslett, and L. P. Hole. Underreporting of Maritime Accidents to Vessel Accident Databases. *Accident Analysis and Prevention,* Vol. 43, 2011, pp. 2053–2063.
6. Psarros, G., R. Skjong, and M. S. Eide. Underreporting of Maritime Accidents. *Accident Analysis and Prevention,* Vol. 42, 2010, pp. 619–625.
7. Qu, X., Q. Meng, and S. Li. Analyses and Implications of Accidents in Singapore Strait. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2273,* Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 106–111.
8. Landsburg, A. C., L. Avery, R. Beaton, J. R. Bost, C. Comperatore, R. Khandpur, T. B. Malone, C. Parker, S. Popkin, and T. B. Sheridan. The Art of Successfully Applying Human Systems Integration. *Naval Engineers Journal,* Vol. 120, 2008, pp. 77–107.
9. Almaz, O. A., T. Altiok, and A. Ghafoori. Risk Analysis of Vessel Traffic in Delaware River. Presented at 91st Annual Meeting of the Transportation Research Board, Washington, D.C., 2012.
10. Dobbins, J. P., and L. M. Jenkins. Geographic Information Systems for Estimating Coastal Maritime Risk. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2222,* Transportation Research Board of the National Academies, Washington D.C., 2011, pp. 17–24.
11. Yin, J. B. Quantitative Risk Assessment of Maritime Safety Management. PhD dissertation. Hong Kong Polytechnic University, 2010.
12. Apostolakis, G. The Concept of Probability in Safety Assessments of 17 Technological Systems. *Science,* Vol. 250, 1990, pp. 1359–1364.
13. Yip, T. L. Port Traffic Risks—A Study of Accidents in Hong Kong Waters. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 44, Issue 5, 2008, pp. 921–931.
14. Shahrabi, J., and R. Pelot. Hierarchical Risk-Based Spatial Analysis of Maritime Fishing Traffic and Incidents in Canadian Atlantic Waters, *Lecture Notes in Geoinformation and Cartography: Geomatics Solutions for Disaster Management,* 2007, pp. 335–350.
15. Kuroda, K., H. Kita, and S. Kono. Mathematical Modelling of Ship Collision Probability. *Memoirs of the Faculty of Engineering* (Kyoto University), Vol. 44, 1982, pp. 135–157.
16. Dobbins, J. P., and M. D. Abkowitz. Development of an Inland Marine Transportation Risk Management Information System. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1782,* Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 31–39.
17. Martin, P. H., E. J. LeBoeuf, E. B. Daniel, J. P. Dobbins, and M. D. Abkowitz. Development of a GIS-Based Spill Management Information System. *Journal of Hazardous Materials,* 2004, pp. 239–252.
18. Dobbins, J. P., and M. Abkowtiz. Use of Advanced Information Technologies for Marine Accident Data Analysis Visualization and Quality Control. *Journal of Transportation Safety and Security,* Vol. 2, No. 1, 2010, pp. 1–13.
19. Fedra, K., and E. Feoli. GIS Technology and Spatial Analysis in Coastal Zone Management. EEZ Technology, 3rd ed., 1998, pp. 171–179.
20. Goralski, R. I., and C. M. Gold. The Development of a Dynamic GIS for Maritime Navigation Safety. ISPRS Workshop on Updating Geospatial Databases with Imagery and 5th ISPRS Workshop on DMGISs, 2007, pp. 47–50.
21. International Maritime Organization. Marine Casualties and Incidents. http://gisis.imo.org/Public/MCI/Default.aspx. Accessed July 17, 2012.
22. Geographic Information System. http://en.wikipedia.org/wiki/GIS. Accessed July 18, 2012.

The Marine Safety and Human Factors Committee peer-reviewed this paper.